Modeling and simulation for SeaWinds-1B system design and performance evaluation

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ABSTRACT

SeaWinds- 1 B is an spaceborne instrument, under design at the Jet Propulsion Laboratory, to accurately measure the speed and direction of ocean surface winds at high resolutions. SeaWinds-l B consists of a scatterometer and a polarimetric wind radiometer. The scatterometer employs range compression to increase the resolution of its sigma-O measurements. The polarimetric radiometer will be used to verify new techniques of passively measuring wind vectors from space. The SeaWinds-l B instrument will also be used to investigate the benefits of combining scatterometer and radiometer data to increase the accuracy of resulting wind products.

Since SeaWinds- 1 B is still in the design phase, there are many system design issues which need to be studied. To aid in such studies, a simulation is being developed which will simulate the operation of the spacecraft (attitude and ephemeris), the scatterometer instrument, and the ground data processing system (sigma-O and wind products). The simulation will provide an estimate of the wind retrieval performance and sigma-O measurement accuracy of the SeaWinds- 1B scatterometer over realistic wind fields and land targets.

Perhaps the most important features of any simulation are the considerations that are used to guide its construction. The SeaWinds- 1 B simulation will incorporate many factors including instrument RF stability, measurement error correlation, geophysical model function errors, and spacecraft attitude stability. Experience from simulations devised for the NASA Scatterometer (NSCAT) and SeaWinds scatterometer wil I he applied to the SeaWinds- 1B simulation.

Keywords: scatterometer, simulation, radar, ocean, winds, SeaWinds

1. INTRODUCTION

A wind scatterometer is a radar instrument which accurately measures the normalized radar cross section, sigma-0, of the ocean's surface from several different geometry's and under various weather conditions. The sigma-0 measurements are used in conjunction with an empirical model function to infer the speed and direction of ocean surface winds. Using a spaceborne scatterometer, global coverage of ocean surface winds can he obtained under nearly all weather conditions within only a few days. The Jet Propulsion Laboratory (JPL) has successfully designed, built, and operated the NASA scatterometer (NSCAT), launched aboard the Japanese ADEOS spacecraft in August 1996, and is currently integrating and testing the SeaWinds- 1 A scatterometer, to be launched aboard the Japanese ADEOS 11 spacecraft in August 1999. The desire to maintain a continuous set of wind data has prompted the development of a third instrument, known as SeaWinds- 1 B, duc to bc launched in the year 2002.

The SeaWinds-1 B instrument consists of a circularly scanning pencil beam scatterometer and a polarimetric wind radiometer. The scatterometer employs range compression to increase the resolution of its sigma-O measurements. The radiometer will he used to investigate techniques of measuring ocean surface winds by passive means. The usc of both scatterometer and radiometer data to improve the accuracy of wind vector measurements will also be examined.

Several simulations were developed for NSCAT. These simulations were used to assist with design trade studies and to determine the expected wind retrieval performance. The highest fidelity NSCAT simulation, known as SuperSim, incorporated a large portion of the ground data processing algorithms and simulated many aspects of the instrument and spacecraft. Instrument data generated post-launch agreed very well with the simulations and gave confidence to our ability to accurately simulate a spaceborne scatterometer. A low resolution simulation for the SeaWinds- I A instrument was also developed and helped guide the design process and predict performance. Currently, a high resolution simulation for the SeaWinds-1A scatterometer is being developed.

Given the number of current scatterometer simulations, it is reasonable to wonder why we are developing yet another simulation for the SeaWinds-l B scatterometer. The primary reason is for flexibility. When performing design trade studies and testing new algorithms it is important to be able to easily modify or replace code and/or change input parameters. Previous simulations were developed for fixed instrument designs and were often coded in optimized, but inflexible, ways to reduce execution times. Trade studies typically involved only minor input modifications such as lowering the transmit power to determine the effect of amplifier aging on expected performance. The SeaWinds-1B simulation will be used to study a much wider range of instrument and algorithm changes. For example, we will be able to use the SeaWinds-1 B simulation to estimate the best wind vector cell resolution that can be obtained while still meeting performance requirements. We will also k able to easily study the effect of adding an additional polarization to a beam. Naturally, we don't want to waste time redeveloping working code or algorithms. Thus, we will inherit from previous simulations where appropriate, but the overall design of the ScaWinds-1 B simulation is new and geared toward flexibility.

After generating simulated data, it is necessary to have the means to analyze and understand the results. Based upon both our simulated and real data experiences, we have devised a rich set of metrics for evaluating instrument wind retrieval performance. These include wind speed bias, RMS wind speed error, and RMS direction error.

2. DESIGNING THE SEAWINDS-1B SCATTEROMETER

The ScaWinds- 1 B instrument is still in the design phase and consequently there are many open design issues which need to be resolved. For a given design, it is necessary to determine the performance of the instrument to verify whether or not the wind retrieval accuracy requirements are being met. Given the novel (to scatterometry) technique of using range compression, it is also important to devise and test algorithms for accurately processing the scatterometer data. In order to accomplish these tasks, it is highly desirable, if not necessary, to have a high fidelity simulation of the instrument. While it is true that many design decisions can be reasonably made without the benefit of a simulation, previous NSCAT experience indicates that scatterometer simulations can provide accurate and useful information for design trade studies, performance estimation, and algorithm development, The NSCAT simulations frequently produced non-intuitive results which, after further analysis, were determine to come from physical and/or technical reasons.

3. SIMULATION PHILOSOPHY

Given the tasks of performing design trade studies, evaluating the wind retrieval performance of the instrument, and testing newly developed algorithms, there are several guiding principles that we used to design the simulation.

First and foremost, the simulation must be flexible. Performing design trade studies invariably involves needing to know the effect of modifying a given set of instrument parameters. A simulation allows this determination to be made by simply varying the input design parameters and observing the effect on the output results, e.g. decrease the transmit power and observe the effect on wind retrieval accuracy. Flexibility is built into a simulation by several means: software design and equation considerations. A certain amount of flexibility can be achieved via thoughtful software design. For example, the SeaWinds-

1 B simulation obtains nearly all of its input parameters from an easily readable and editable parameter file. Although this approach requires some extra programming, it allows instrument and processing parameters to be easily found and changed. Good modular software design also makes the simulation more flexible since newly developed algorithmic functions easily can be swapped in with the knowledge that they will be used correctly throughout the simulation. Equation considerations are necessary to make sure that the simulation will produce meaningful results for all values of the input parameters. It is essential that all assumptions and approximations be fully understood so that modifying the input parameters will not end up invalidating the equations using those input parameters. Accommodating ranges of input parameters makes developing a flexible simulation more difficult than developing a simulation for a single point design.

The second guiding principle we used is that the simulation should mimic the expected ground processing system and have identical output product organization and formats. This has two important benefits. Any analysis tools developed for the simulation can be immediately applied to real mission data. Also, the simulation can double as a ground processing system for off-line processing of data.

Thirdly, we would like to design the simulation so that it can be up and running quickly and yet be able to easily accommodate enhancements and improvements. In other words, quickly develop a working skeleton while keeping in mind the nature of future changes and increases in fidelity.

4. SIMULATION ORGANIZATION AND CAPABILITIES

The SeaWinds- l B simulation has been organized as a suite of sequential programs each of which reads in the output of the previous program, performs some value added processing, and saves the results to tile. There are several compelling reasons to organize this, or any large simulation, in such a way. Firstly, it allows the user to examine intermediate data easily since they are written out to file. Secondly, modified processing can take place at an appropriate stage. For example, to process sigma-O data to different wind field resolutions, it is not necessary to simulate the operation of the instrument again, nor reconvert instrument parameters, to engineering units, nor recalculate sigma-O. Only collocation and wind retrieval need to be reperformed at the desired resolution. This means that a multi-resolution study can be performed by generating a single set of sigma-O data and then repeatedly running the collocation and wind retrieval programs at the desired resolutions. This significantly reduces the time necessary to perform such analyses.

In this section, wc describe each of the programs of the simulation, in logical order, and indicate the capabilities of each. Figure I shows a block diagram of the simulation noting key inputs and outputs of each program.

4.1 Input analysis tools

Although technically not part of the simulation, input analysis tools are a necessary part of simulating the SeaWinds- lB instrument. Input analysis tools are software tools which help determine some of the inputs to the simulator. For example, a separate program was written to optimize the timing characteristics (pulse repetition frequency, pulse width, etc.) of the instrument. The timing information calculated from this program arc then used as inputs 10 the simulation. Of course, they can bc modified as desired to study their effects on the performance of the instrument.

4.2 Instrument simulator

The instrument simulator is responsible for generating realistic looking instrument telemetry. This entails the following steps: (l) simulate the ephemeris of the host spacecraft using an orbit simulator, (2) simulate the attitude of the host spacecraft, (3) simulate the rotation of the antenna dish, (4) calculate the location of each measurement on the earth's surface, (5) from an input wind field, determine the wind vector at the measurement location, (6) using a geophysical model function, determine the expected sigma-0 value at the measurement location, (7) convert the expected sigma-O value to a received power, using the radar equation

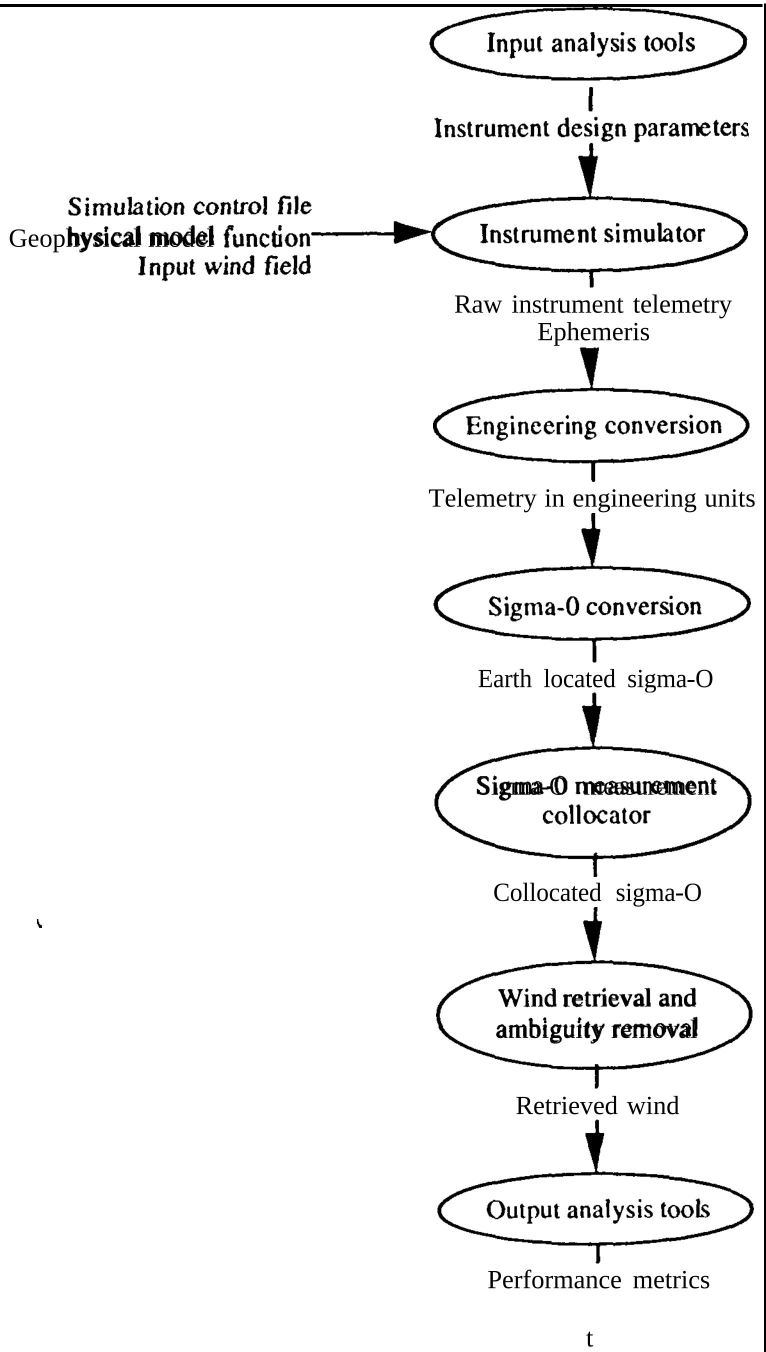


Figure 1. Simulation Flow Diagram

and simulated measurement errors, (8) convert measurement, instrument, and spacecraft parameters into telemetry format and save.

The outputs of the instrument simulator are the raw instrument telemetry and an ephemeris file containing the spacecraft location and velocity at fixed time increments.

4.3 **Engineering conversion**

The engineering conversion simply converts engineering parameters from the quantized telemetry format into engineering units (volts, Watts, dB, etc.). This step can initially be eliminated by defining the raw telemetry to be in engineering units.

4.4 **Sigma-O conversion**

The purpose of the sigma-O converter is to convert the received signal power measurement to sigma-O. This ‘is done via the radar equation:

$$\sigma_0 = \frac{P_{r(S)}}{X} \tag{1}$$

where $P_{r(S)}$ is the received signal power and

$$X = \frac{P_t G_a^2 G_r \lambda^2 A}{R^4 L (4\pi)^3} \tag{2}$$

where

P_t = transmit power for the measurement pulse
G_a = antenna gain for the measurement cell
G_r = receiver gain
λ = transmit wavelength
A = effective area of the measurement cell
R = slant range to measurement cell
L = system losses

The reeeived signal power is calculated by subtracting an estimate of the received noise power from the signal plus noise measurement:

$$P_{r(S)} = \left(P_{r(S+N)} - P_{r(N)}\right) \tag{3}$$

Many of the parameters used to calculate X require excessive computation. For example, the calculation of the effective area of a cell is an extremely complicated calculation involving the baseband frequency range of the cell (in high resolution mode), the antenna pattern, the spacecraft ephemeris, and the spacecraft attitude. Initially, low fidelity approximations are used to rapidly assess instrument performance. Comparisons with high fidelity calculations can then be used to study the impact of the simplified approximations. Such studies can aid in the design of the ground data processing system.

4.5 **Sigma-O measurement collocator**

At this point, the instrument measurements have been converted to sigma-O measurements with specific locations on earth. The purpose. of the sigma-O measurement collocator is to place these sigma-O measurements into an along track/cross track grid with fixed distance spacing on the earth’s surface. It is these collocated measurements that will be used by the wind retrieval algorithm to determine the wind speed and direction for each element in the along track/cross track grid. The collocation algorithm requires knowledge of the spacecraft location and velocity in order to construct the grid.

4.6 **Wind retrieval and ambiguity removal**

Wind retrieval involves converting each set of collocated sigma-O measurements into an ambiguous set of wind vector solutions. To retrieve winds, we must first invert the geophysical model by numerically finding the continuous set of wind speeds and directions which are most likely to produce the given measurement of sigma-O. From this continuous set of likely wind vector solutions, we select the four wind vectors which are most likely. These four solutions are referred to as ambiguities.

Ambiguity removal is the process of selecting a single ambiguity for each wind vector cell to be the retrieved wind vector. We use a median filter to perform ambiguity removal. The median filter selects the ambiguity which has the minimum summed vector difference between itself and the selected vectors of the neighboring wind vector cells in an NxN region. In essence, the median filter selects the ambiguity that makes a wind vector cell "most similar" to its neighbors. In order to start the median filtering process, an initial wind field must be chosen. The initial wind field is determined by applying a maximum likelihood estimator to the ambiguities of each wind vector cell. The ambiguity with the highest likelihood of being nearest to the true wind direction is used to initialize the wind vector cell. Once an initial wind field is determined, the median filter is repeatedly applied to the wind field until it converges.

4.7 Output analysis tools

After the simulation has produced an output wind swath, we *need* to evaluate the performance of the simulated instrument. We have developed a set of metrics which can statistically compare the output wind swath with the input wind field. Other analysis tools are used to examine intermediate products to determine information such as the distribution of sigma-O. Yet other analysis tools provide information on measurement geometry, such as the average number of sigma-O measurements per wind vector cell as a function of cross track distance. The full suite of output analysis tools enable us to assess the performance of the instrument, debug the simulation (if necessary) and, in the future, analyze real mission data returned by the instrument on-orbit.

5. MODELING

In order to accurately calculate sigma-O from the radar equation (Eq. 1), we need to accurately simulate the received signal power, $P_{r(S)}$, and accurately calculate the factor X. Since the received signal is noise-like, there is error inherent in measuring its power over a finite time and bandwidth. Accurate calculations of the factor X depend upon instrument calibration and data processing accuracy.

The error in measuring a noise-like signal is referred to as communication noise and is well characterized. We model communication noise as gaussian distributed additive noise and represent it by its normalized standard deviation, K_{pc}.

The error in X can be modeled as follows:

$$\mathbf{X}_{meas} \equiv X_{true} + B + r(t) \tag{4}$$

where X_{meas} is the measured or calculated value of X used to calculated sigma-O, X_{true} is the true, but unknown, value of X, B is a fixed bias error and r(t) is a time varying error.

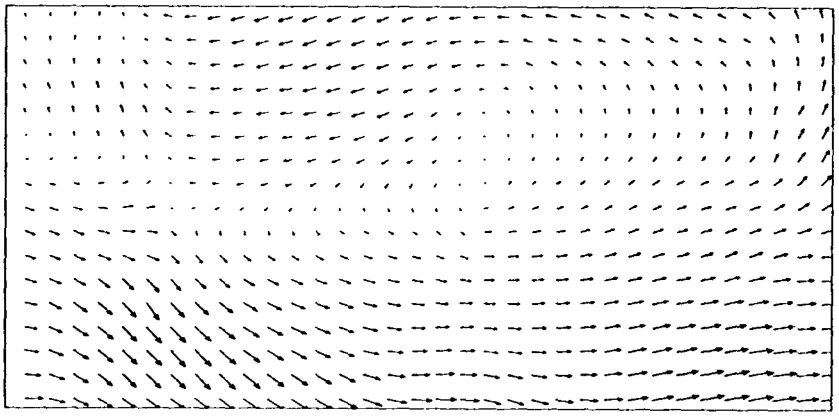
It is expected that the fixed bias error, B, will be detected and removed post launch. However, the term is kept in our simulation to study the effects of not entirely removing a bias error. Incidentally, fixed bias errors may bc different for different beams leading to a relative bias in addition to an absolute bias.

The time varying error, r(t), is modeled as gaussian distributed additive noise and is represented by its normalized standard deviation, K_{pr}. The value of K_{pr} is estimated from instrument calibration data and from design knowledge. Some contributing terms to K_{pr} arc RF component instabilities, antenna gain variations due to temperature, and errors in the measurement of the transmit power and/or receiver gain[1].

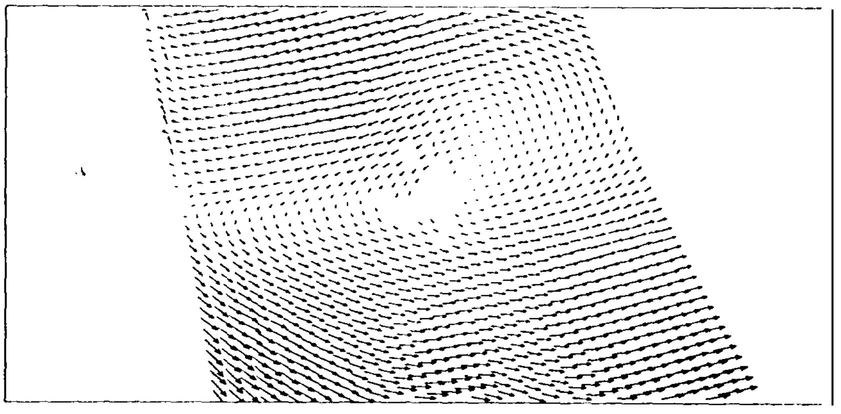
6. SAMPLE RESULTS

Since wc arc in the early stages of developing the simulation, we do not have high radiometric fidelity. However, we currently have the ability to simulate the flight of the SeaWinds- 1 B scatterometer over an

NSCAT derived wind field, retrieve noise-free measurements of sigma-O, grid the sigma-O values at variable resolutions, retrieve an ambiguous wind swath, and perform ambiguity removal on the ambiguous wind swath to obtain a retrieved wind swath. Figure 2 shows a comparison of the input wind field (at 1" x 1" resolution) and the retrieved wind swath (at 50 km x 50 km resolution) for a fraction of an orbit. Both the input wind field and output wind swath are plotted at the same resolution. The swath only covers a portion of the input wind field.



Input Wind Field



Output Wind Swath

Figure 2. Comparison of Input Wind Field and Output Wind Swath

7. FUTURE WORK

In the future, we plan [o increase the fidelity of the simulation to the point where it can be used to test new data processing algorithms. As we develop the simulation, we want to be certain that it continues to mimic the expected data processing system and products so that the simulation can be used for analyzing real data and also be used as a ground data processing system.

8. CONCLUSION

An organized simulation effort can be extremely beneficial to the development of a spaceborne scatterometer. If designed properly, it can have many applications including assisting with system design trade studies, testing new algorithms, analyzing on-orbit data, and processing data.

9. REFERENCES

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